Fermi National Accelerator Laboratory

TM-1600

A Main Ring Bunch Length Monitor by Detecting Two Frequency Components of the Beam

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A MAIN RING BUNCH LENGTH MONITOR BY DETECTING TWO FREQUENCY COMPONENTS OF THE BEAM

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Abstract

The bunch length is measured by detecting two revolution frequency harmonics of the beam and taking the ratio of their amplitudes. Two heterodyne receivers have been made to detect them, one at 53MHz and the other at 159MHz. These signals are picked-up by a stripline detector. An analog circuit provides a signal proportional to the bunch length. The monitor measures variation of the bunch length as a function of time in the Main Ring. The measured signal, which sometimes shows that the bunches are tumbling in phase space, can be damped by feedback to the RF amplitude modulator.

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1. Introduction

The new bunch spreader project [1],[2] for the Main Ring is in progress. The project increases the longitudinal emittance, and hence the bunch length, in order to raise the threshold beam current of instabilities in fixed target mode. A bunch length monitor is needed to measure the effect of the bunch spreader. Variations of the bunch length must be easily and clearly read from the monitor in real time.

In addition to bunch length spreading, the proton bunches suffer the bunch rotation process [3] in colliding mode, where proton bunches are narrowed to make high density antiprotons by a manipulation of the RF voltage. It is necessary to monitor the bunch length during the bunch rotation process, where the bunch length varies dramatically.

The bunch length measurement from a mountain range photograph is unsuitable, because the measurement is not clear or real time. The bunch length is also measured from a stored bunch shape using a computer [4]. This measurement is adequate for a single bunch, but not for multi-bunch operation in the Main Ring. It will be difficult to gate and extract an individual bunch, and it takes time to average data of a bunch especially when bunches are unstable and their individual shapes are different.

Though we will find a brief description about this bunch length monitor in ref. [2], this note describes the detailed performance of the monitor. This note is arranged as follows. A principle of the measurement is given in the next section. Design and performance of the bunch length monitor are presented in sections 3 and 4. Beam observations using the monitor are shown in section 5 and discussions about the measurements are seen in section 6.

2. Principle[5]

Let us model the N bunches (N>1) as Gaussian longitudinal charge distributions, separated by a fixed time ($T_0 = 1/f_0$) . The signal produced by such a pulse train on an ideal beam pickup can be written as

$$V(t) = \frac{s}{\sqrt{2\pi}\sigma_t} \sum_{n=1}^{N} I_n \ \mathrm{EXP} - \left[\frac{(t-nT_0)^2}{2\sigma_t^2}\right] , \tag{1}$$

where $V(t)$ is the output voltage waveform from the pickup, s is the sensitivity, σ_t is the rms bunch length in unit of time and I_n are the individual bunch currents. Taking the Fourier Transform of (1) yields

$$V(\omega) = \frac{s}{2\sqrt{2\pi}} \; EXP-\left[\frac{\omega^2\sigma_t^{\;2}}{2} \right] \sum_{n=1}^{N} I_n \; e^{j\omega nT_0} \; \Phi\left[\frac{nT_0}{\sqrt{2}\,\sigma_t} - j\frac{\omega\sigma_t}{\sqrt{2}}\right], \tag{2}$$

where $\Phi(z)$ is the error function. The beam spectrum is dominated by multi-poles of the RF frequency (f_0 = 53MHz). We therefore evaluate the peak height of $V(\omega)$ at those frequencies. The equation (2) becomes

$$V(m\omega_0) = \frac{s}{2\sqrt{2\pi}} \; EXP -\left[\frac{2\pi^2 m^2 \sigma_t^{\;2}}{T_0^{\;2}} \right] \sum_{n=1}^{N} I_n \; \Phi\left[\frac{-nT_0}{\sqrt{2}\,\sigma_t} - j\frac{\omega\sigma_t}{\sqrt{2}}\right], \tag{3}$$

where m is an integer and $\omega_0 = 2\pi f_0$. In the σ_t/T_0 region of interest (N > 8 and $4\sigma_t < T_0$), (3) reduces to

$$V(m\omega_0) = 2V_{dc} \; EXP - \left[\frac{2\pi^2 m^2 \sigma_t^{\;2}}{T_0^{\;2}} \right], \text{ where} \tag{4}$$

$$V_{dc} = \frac{s}{4\sqrt{2\pi}} \sum I_n \tag{5}$$

is the DC response of the beam. Solving for σ_t/T_0 in the case of DC vs. m=1 yields

$$\frac{\sigma_t}{T_0} = \sqrt{\frac{1}{2\pi^2} \; LN\left[\frac{2V_0}{V(\omega_0)} \right]} \; . \tag{6}$$

When detecting the frequencies of m=1 vs. m=λ, the normalized bunch length (σ_t/T_0) is given as

$$\frac{\sigma_t}{T_0} = \sqrt{\frac{-1}{2\pi^2(\lambda^2-1)} \; LN\left[\frac{V(\lambda\omega_0)}{V(\omega_0)} \right]} \; . \tag{7}$$

In an actual measurement, the 95% interval of the beam distribution, referred to as the full bunch length $4\sigma_t$, is the quantity of interest. Since T_0 is almost constant in the Main Ring, the rms bunch length can be replaced by the full bunch length. Therefore, we use the full bunch length instead of the rms bunch length in all measurements.

3. Design

3-1. *Selection of Detected Frequencies*

In the frequency response of actual pickups, the sensitivity at each frequency is different. So, the range of detected frequencies is limited and the gain factor between two detectors must be compensated. Two detection schemes are considered using pickups already installed.

The DC component is available from a DCCT [6]. The DCCT supplies a DC-1kHz signal and is directly used for this measurement. It has three outputs in order to cope with variation of beam intensity and a wide linear range of about 60 dB within 2% linearity. The other partner for the DCCT signal is the 53 MHz signal coming from a BPM RF module [7]. The sum signal output of the module will be used for this 53 MHz detection. Since the signal is a pulse with repetition rate of the revolution frequency (47kHz), an integration of the pulse train is needed to match the signal to the DCCT.

On the other hand, a stripline electrode with length l is a broad-band resonator with multiple resonant frequencies of

$$f_m = \frac{2n + 1}{4l} v , \tag{8}$$

where v is the velocity of beam and n is the integer including zero. The stripline installed at E48 has the resonant frequencies of 53MHz, 159MHz, 265MHz and so on. The signals from the upstream and downstream ends of the stripline are combined in order to detect the longitudinal component of both protons and antiprotons.

In order to determine the pickup and the detected frequencies, let us compare the two detections described above, i.e. the DC/53MHZ case and the 159MHz/53MHz case which corresponds to $\lambda=3$ in eq.(7). Figure 1 shows the amplitude ratio of the two frequency components as a function of the bunch length. The interesting bunch length in the Main Ring is in the range of 1 to 10 nsec. When the bunch length is short enough, the amplitude ratio is almost one in both cases. The DC/53MHz case requires more severe linearity and stability for detections than the 53MHz/159MHz case. For example, the amplitude ratio is 1.003 in the DC/53MHz case and 1.03 in the 159MHz/53MHz case when the bunch length is 1 nsec. At the bunch length of 10 nsec, the ratio becomes 0.063 in the 159MHz/53MHz case, which requires a dynamic range of at least 24dB to detect both amplitudes. Detection of higher frequencies than 159MHz requires much wider dynamic range for detectors. If we select the DC/53MHz case, however, we will have trouble with different transient responses because of the different types of detectors. Therefore, the 159MHz/53MHz case is selected for the bunch length monitor in the Main Ring.

3-2. Specifications

The Main Ring handles various numbers of bunches. The proton bunches are almost fully occupied in 1113 RF-buckets in the fixed-target mode. In the antiproton production cycle, 81 or 3x81 proton bunches are accelerated. When the bunches are coalesced and transfered to the Tevatron, only 11 proton and antiproton bunches are accelerated. Beam intensity per bunch is different between protons and antiprotons. The dynamic range of the beam intensity is about 60dB.

In order to measure the bunch length in the Main Ring, the following specifications for two detectors with the same performance would be required.

1. minimum detectable level	-80 dBm
2. dynamic range	90 dB
3. accuracy	1 %
4. frequency response	10 kHz

The minimum signal is observed in the 159MHz component during antiproton coalescing. The dynamic range of 90 dB is caused by the beam intensity variation plus the amplitude ratio between two components. The accuracy of at least 1% is needed to detect a short bunch length of 1 nsec. The 10kHz response comes from detecting harmonics of the synchrotron frequency and measuring transient beam response at such time like bunch rotation.

4. Performance

4-1. Heterodyne Receivers

Two heterodyne receivers are employed to detect the 53 and 159 MHz components of the beam. The main advantages of a receiver are high sensitivity and wide dynamic range, and its disadvantage is the need for a complicated circuit. Figure 2 shows the block diagram of the bunch length monitor composed of two heterodyne receivers and an analog circuit named a normalizer. The heterodyne receivers have two stages of frequency mixing to get high sensitivity. The intermediate frequencies (IFs) of 10.7MHz and 455kHz are used since cheap and small ceramic filters are commercially available [8].

The beam signal coming from the stripline pickup in the tunnel to the F0 RF building is split after passing through a programmable attenuator, one half passes through the 53 MHz Band Pass Filter (BPF) and the other half through the 159 MHz filter. The bandwidth of the BPFs are matched at 1MHz as shown in Figure 3 to get comparable transient responses. However, the insertion loss between them is different by 0.6dB, along with the difference of the transmission loss of the cable from the tunnel to the F0, must be compensated.

The 53MHz RF signal comes from the LLRF, which changes from 52.8MHz to 53.1MHz in the Main Ring cycle and is synchronized with the bunches. The triple frequency of the RF is made by using two double-balanced mixers (Mini-Circuits, SRA-1) to synchronize the RF with the 159MHz beam signal. The RF and the triple RF signals are mixed with the 10.7MHz local crystal oscillator. The difference frequencies of the IF output of the RF mixers, i.e. 42.3MHz and 148.3MHz are filtered and amplified up to LO level of the 1st mixers which are mixed with the 53MHz and 159MHz beam signals. In order to prevent the signal of the 10.7MHz oscillator from entering the IF outputs of the 1st mixers, a 10.7MHz trap (Band Reject Filter) is inserted in the LO lines and the oscillator itself is electrically shielded. The 10.7MHz beam signals with constant frequency are obtained at the IF outputs of the 1st mixers.

The 2nd mixers convert the 10.7MHz beam signal into 455kHz with the 10.245MHz local oscillator. The 455kHz signal is amplified and filtered by ceramic filters (Murata/Erie CFW455B) with a bandwidth of 22kHz. This 2nd stage of mixers increases the sensitivity and the dynamic range to about 60dB. The upper level is limited by saturation of the mixers and the lower by amplifier noise. The subsequent 455kHz detector is a full-wave rectifier [7], where a bipolar pulse made from an input signal acts as a switch at a mixer and the input signal is rectified there. The time constant of the 455kHz detectors is 10μsec, which means that the detector follows variation of the bunch length with two-turn delay and 2% error. The linear range of this detector is about 40dB as shown in Figure 4.

The performance of the receivers is summed up in Table 1. Transfer characteristics of the receivers are shown in Figure 5 and 6. Continuous waves (CW) from a signal generator were used in those measurements.

4-2. Normalizer

The normalizer section is composed of two logarithmic amplifiers (B.B., 4127s), a differential amplifier and a square rooter (AD534). The block diagram is shown in Figure 7. The log amplifiers accept a signal of 60dB range (10mV-10V) and provide an output signal with frequency response of more than 5 kHz. The calculated transfer function of this section is

$$Y = 8.17 \sqrt{\mathrm{LOG}\left[\frac{V_1}{V_3}\right]} , \tag{9}$$

where Y is the output voltage of the normalizer in volts, V_1 is the amplitude of 53MHz component and V_3 is that of 159MHz one. The measured output voltage agrees with the calculated value within 5%, but maximum Y is 10 V. From eq. (7) with $\lambda=3$ and eq. (9), the relation between the bunch length and Y is given as

$$4\sigma_t \text{ (nsec)} = 1.12 \text{ Y}. \tag{10}$$

The output is also available for square of the bunch length, which is proportional to the longitudinal emittance [9] assuming that the frequency dispersion function and the RF voltage are constant.

5. Beam Observation

Responses of each stage of the heterodyne receiver were checked during an antiproton production cycle. Figure 8 shows the response to 81 bunches with a total intensity of 1.7×10^{12}. After passing through the 53MHz BPF, the beam signal is not a CW but a pulse-modulated rf wave . The duration of the signal is 1.5 μsec. Since the settling time is 100 nsec at both channels, the amplitude is independent of the number of bunches more than 5. The duration is stretched to 5 μsec at the 10.7MHz stage and the signal becomes almost CW at the 455kHz stage, because the bandwidth of this stage is comparable to the revolution frequency.

A gain difference between the two detectors produces an offset in the bunch length. The gain was roughly adjusted by inserting a fixed attenuator in front of the 53MHz BPF and precisely adjusted by the gain control of the 455kHz detector at extraction where the bunch length is minimum and most sensitive to the gain difference.

Figure 9 shows a typical measured bunch length during acceleration of 81 bunches, which agrees with the expected full bunch length [2]. The noise in the measured bunch length is dominated by real bunch length fluctuations. Three photographs in Figure 10 show close views of the fluctuations and dramatic changes of the bunch length. At injection, we observe a large modulation of the bunch length in Figure 10-(a). The modulation damps gradually, keeping the average bunch length constant. Around transition, the bunch length becomes short and the frequency of the fluctuations decreases approaching transition as shown in Figure 10-(b). Figure 10-(c) shows how the bunch length varies during the bunch rotation process. The net RF voltage is suddenly reduced from the normal value to a low voltage. The bunch length begins to increase from 2.6 nsec up to 8.4 nsec for 3 msec. Then the RF voltage is raised back to the normal value and the bunch length goes down to 1.0 nsec in 1.4 msec. A small dip of the RF voltage is due to beam loading at extraction.

The frequencies of the bunch length fluctuations can be measured with a spectrum analyzer (hp 3562A). The analyzer is externally triggered. A frequency resolution is determined by the gate time of the analyzer. Two main components are observed clearly. The measured frequency of the highest amplitude agrees with twice the small amplitude synchrotron frequency

($2f_s$). This phenomenon shows that the bunches rotate in phase space and modulate the bunch length with the frequency of $2f_s$ as illustrated in Figure 11. The second peak corresponds to f_s, which is 10dB below the 1st peak, and may be due to asymmetric $2f_s$ oscillations.

The detected $2f_s$ oscillations can be suppressed by feedback to the RF amplitude program, because the bunch length oscillation is mainly caused by mismatch between an RF bucket and the bunch. The output signal of the monitor passes through a High Pass Filter to eliminate DC component and its phase shifted by 90 deg. to make a damping force. After the signal is amplitude modulated and gated by analogue multipliers (AD534), the resultant signal is summed with RF amplitude control voltage and sent to the RF amplifiers. The feedback test was done at flattop of a three-batch operation cycle, where $2f_s$ is constant at 160Hz. Figure 12 demonstrates the effect of this damping. The damping time was 30 msec or five oscillations. When the feedback gain is raised to get faster damping, an anti-damping occurred. Further study is needed when this feedback is used in daily operation.

6. discussions and conclusion

A prototype of the bunch length monitor has been made and successfully tested. The detected output voltage of the monitor shows variation of the bunch length as a function of time. The monitor is used not only during the bunch spreader experiment [2] but also during tuning the Main Ring beam. Some improvements for the monitor resulted from the experiences.

The measured dynamic range of the system is 30dB. However, when signal level is low, the S/N of the output gets worse. The level of the input signal will be automatically controlled by the programmabble attenuator to detect in a good S/N region and to cope with intensity variation. Next, when frequency was swept from 52.8MHz to 53.1MHz, the output level of the 159MHz detector varied by 5%. This is caused by unevenness of the 159MHz and the 148.3MHz BPF. The improved BPFs have flat response of 0.1dB or 1%. Third, the signal of the 10.7MHz oscillator was observed in the 10.7MHz IF section. The level is about -60dBm, which restricts the sensitivity and affects linearity at low signal level. A stronger shielding is required for each section of the monitor, especially for the oscillators.

The Gaussian distribution is assumed in this measurement, however, the real bunch shape is not precisely Gaussian. For example, the bunches are strongly disturbed and oscillate at injection. The bunch intensity and its shape seem to be different from bunch to bunch. In these cases, it is not easy to measure the bunch length from the real bunch shape. The different bunch shapes yield different beam spectra. Therefore, the detected bunch length gives different values, which would be a problem. Even so, the monitor always gives an average bunch length over the whole bunches.

Our concluding remarks are as follows.

(1) The monitor measures not only the average bunch length over many bunches, but also the quadrupole oscillations with a response of 10 kHz.

(2) The detected quadrupole oscillations can be used for damping by feedback to the RF amplitude.

(3) This monitor is indispensable for the bunch spreader.

(4) This is a useful tool for monitoring a longitudinal behavior of bunches in daily operations.

Acknowledgement

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References

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[2] G. Jackson and T. Ieiri, "Stimulated Longitudinal Emittance Growth in the Main Ring", FERMILAB-Conf-89/83

[3] P. Martin and D. Wildman, "Bunch Coalescing and Bunch Rotation in the Fermilab Main Ring: Operational Experience and Comparison with Simulations", FERMILAB-Conf-88/87

[4] C.D. Moore et al., "Single Bunch Intensity Monitoring System using an Improved Wall Current Monitor", to be published in Proceedings of the 1989 IEEE Particle Accelerator Conference

[5] R. Siemann, private communication

[6] R. Webber, private communication

[7] S. Jachim, R. Webber and R. Shafer, "An RF Beam Position Measurement Module for the Fermilab Energy Doubler", IEEE NS-28,3 (1981) 2323

[8] H. Ishii, private communication

[9] S. Ohnuma, "The Bucket and the Beam", TM-1381, (January 22, 1986)

Table 1. Performance of Heterodyne Receivers

1. RF MIXER	
RF INPUT LEVEL	- 5 dBm @ 53 MHz
	-10 dBm @ 159 MHz
2. 10.7 MHz I.F. AMPLIFIER	
GAIN	21.5 dB
BANDWIDTH	280 kHz @ -3 dB
MAXIMUM LINEAR OUTPUT	0 dBm
OUTPUT NOISE LEVEL	- 60 dBm
3. 455 kHz I.F. AMPLIFIER	
GAIN	23 dB
BANDWIDTH	22 kHz @ -3 dB
MAXIMUM LINEAR OUTPUT	+ 23 dBm
OUTPUT NOISE LEVEL	- 43 dBm
4. 455kHz DETECTOR	
LINEAR RANGE	40 dB
RESPONSE TIME	40 μsec @ 98% value
MAXIMUM INPUT LEVEL	+ 13 dBm

Figure Caption

Figure 1. Amplitude ratio of the frequency components as a function of bunch length for DC/53 MHz and 159 MHz/53 MHz cases

Figure 2. Block diagram of the bunch length monitor

Figure 3. Frequency response of (a) 53MHz and (b) 159MHz band-pass filters, both scales are H: 5MHz/div, V: 10dB/div

Figure 4. Static response of the 455 kHz detector

Figure 5. Static response of the 53 MHz heterodyne receiver

Figure 6. Static response of the 159 MHz heterodyne receiver

Figure 7. Block diagram of the bunch length normalizer section

Figure 8. Beam responses of the 53MHz heterodyne receiver
a) 53MHz beam signal after passing through the BPF, H:500nsec/div, V:100mV/div without an attenuator
b) 10.7MHz IF output with 30dB input attenuation, H: 1μsec/div, V:50mV/div
c) 455kHz IF output with 30dB input attenuation, H: 2μsec/div, V: 50mV/div

Figure 9. Measured bunch length as a function of time with the current of the dipole bus, H: 0.4sec/div, V: 3nsec/div

Figure 10. Close views of the bunch length
a) at injection, H: 2msec/div, V: 2.3nsec/div
b) around transition, H: 10msec/div, V: 0.6nsec/div
c) during the bunch rotation process just prior to extraction, lower two trace is the net RF voltage, H: 1msec/div, bunch length: 2.3nsec/div

Figure 11. Bunch rotation in phase space and bunch length modulation

Figure 12. Damping the $2f_s$ oscillations at flattop of three-batch mode, with beam current and the RF voltage
H: 425msec/div, bunch length; 2.5nsec/div
a) without feedback
b) with feedback on between 3.8 - 4.8 sec

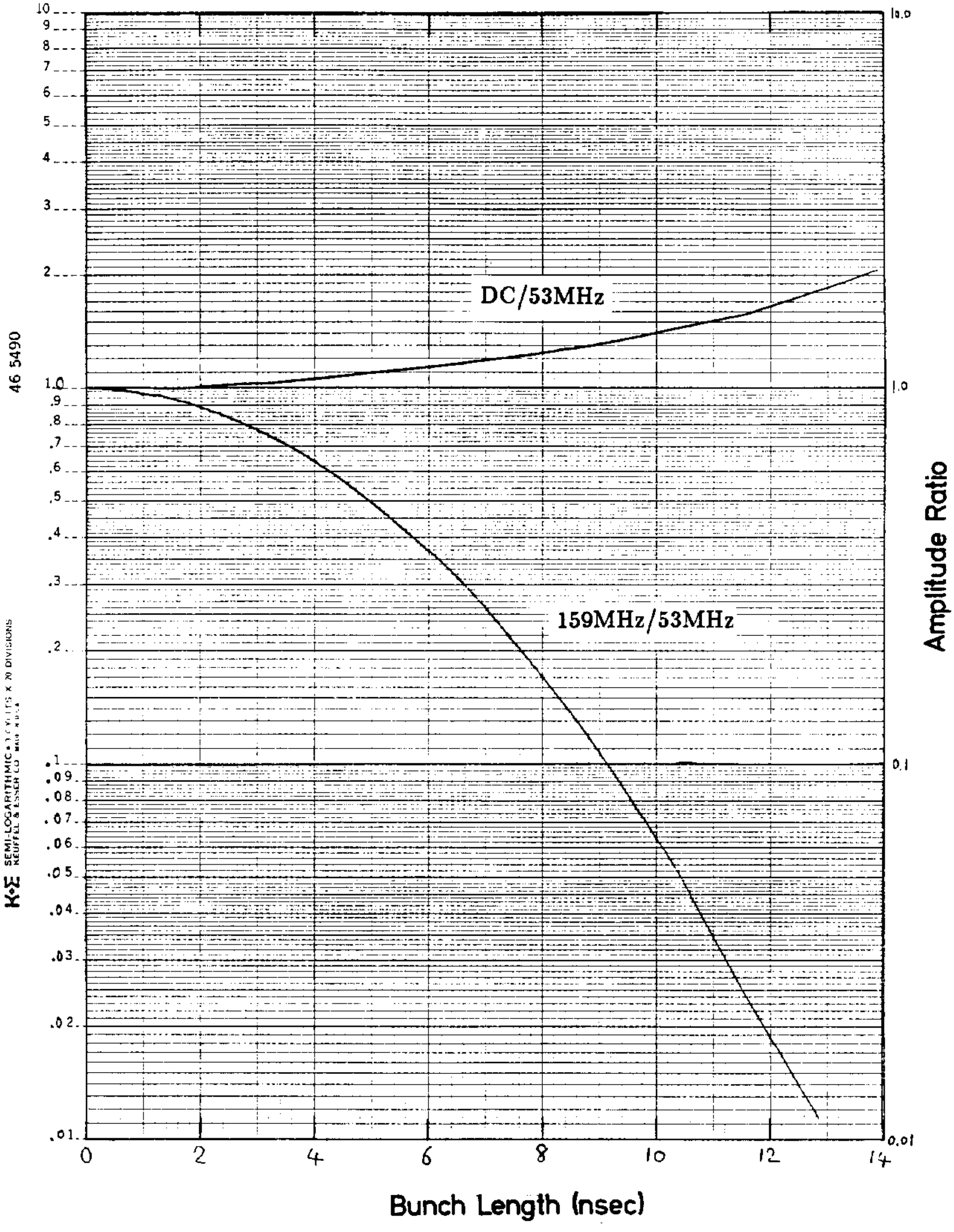

DC/53MHz
159MHz/53MHz
Amplitude Ratio
Bunch Length (nsec)
0
2
4
6
8
10
12
14
10
1.0
0.1
0.01
46 5490
K•E SEMI-LOGARITHMIC • 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.

Figure 1

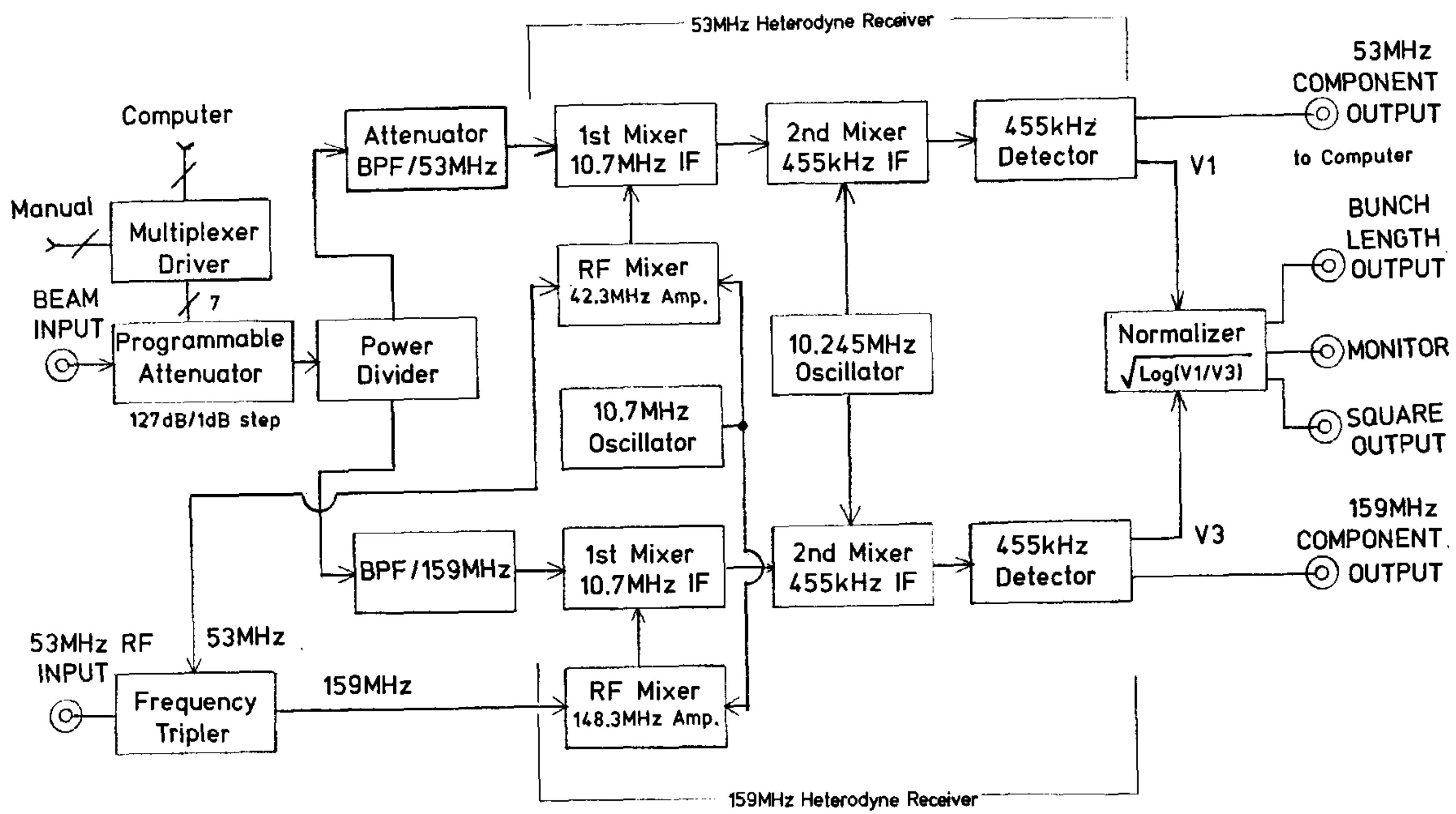
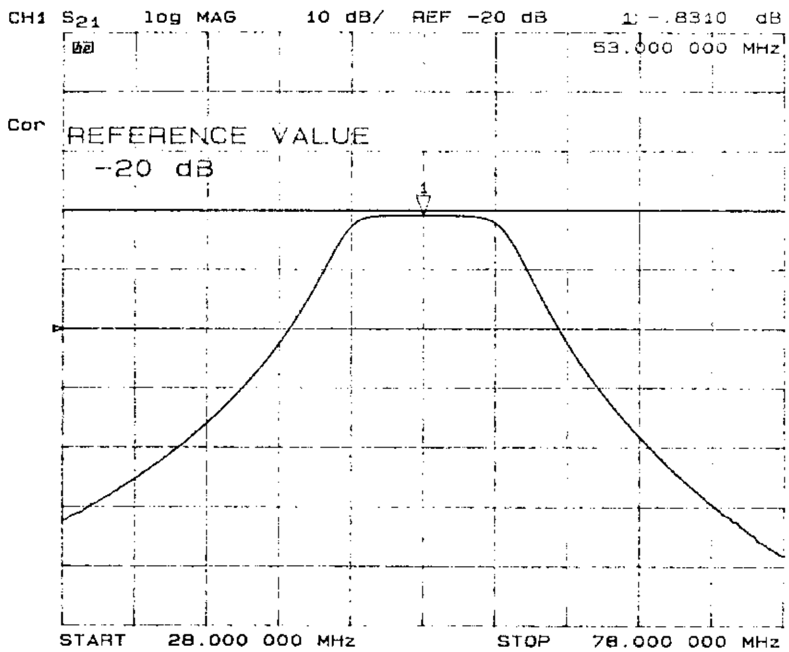
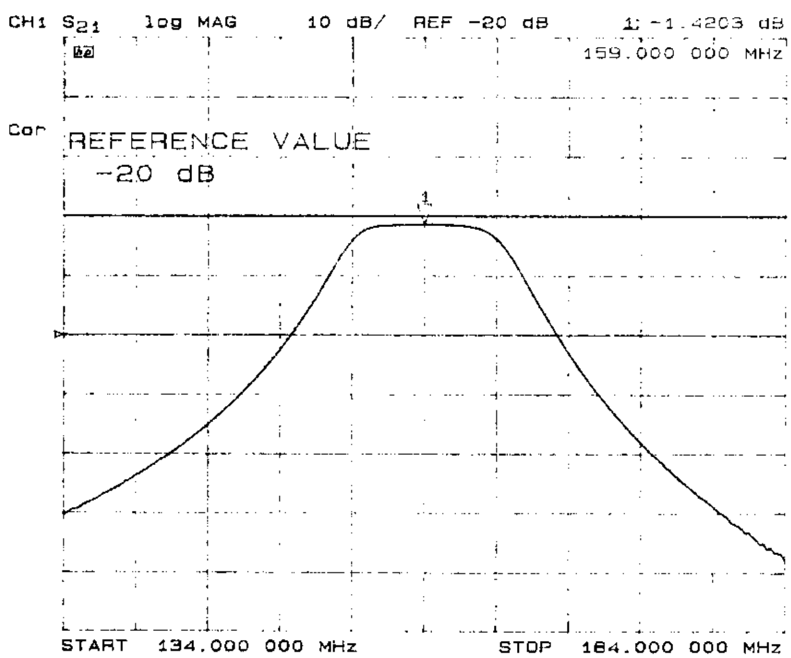

53MHz Heterodyne Receiver
Computer
Manual
Multiplexer Driver
7
BEAM INPUT
Programmable Attenuator
127dB/1dB step
Attenuator BPF/53MHz
Power Divider
1st Mixer 10.7MHz IF
RF Mixer 42.3MHz Amp.
10.7MHz Oscillator
2nd Mixer 455kHz IF
10.245MHz Oscillator
455kHz Detector
V1
53MHz COMPONENT OUTPUT
to Computer
BUNCH LENGTH OUTPUT
Normalizer $\sqrt{\mathrm{Log}(V1/V3)}$
MONITOR
SQUARE OUTPUT
BPF/159MHz
1st Mixer 10.7MHz IF
2nd Mixer 455kHz IF
455kHz Detector
V3
159MHz COMPONENT OUTPUT
53MHz RF INPUT
53MHz
Frequency Tripler
159MHz
RF Mixer 148.3MHz Amp.
159MHz Heterodyne Receiver

Figure 2


CH1 S21 log MAG 10 dB/ REF -20 dB 1: -.8310 dB
53.000 000 MHz
Cor
REFERENCE VALUE
-20 dB
START 28.000 000 MHz STOP 78.000 000 MHz

a)


CH1 S21 log MAG 10 dB/ REF -20 dB 1: -1.4203 dB
159.000 000 MHz
Cor
REFERENCE VALUE
-20 dB
START 134.000 000 MHz STOP 184.000 000 MHz

b)

Figure 3

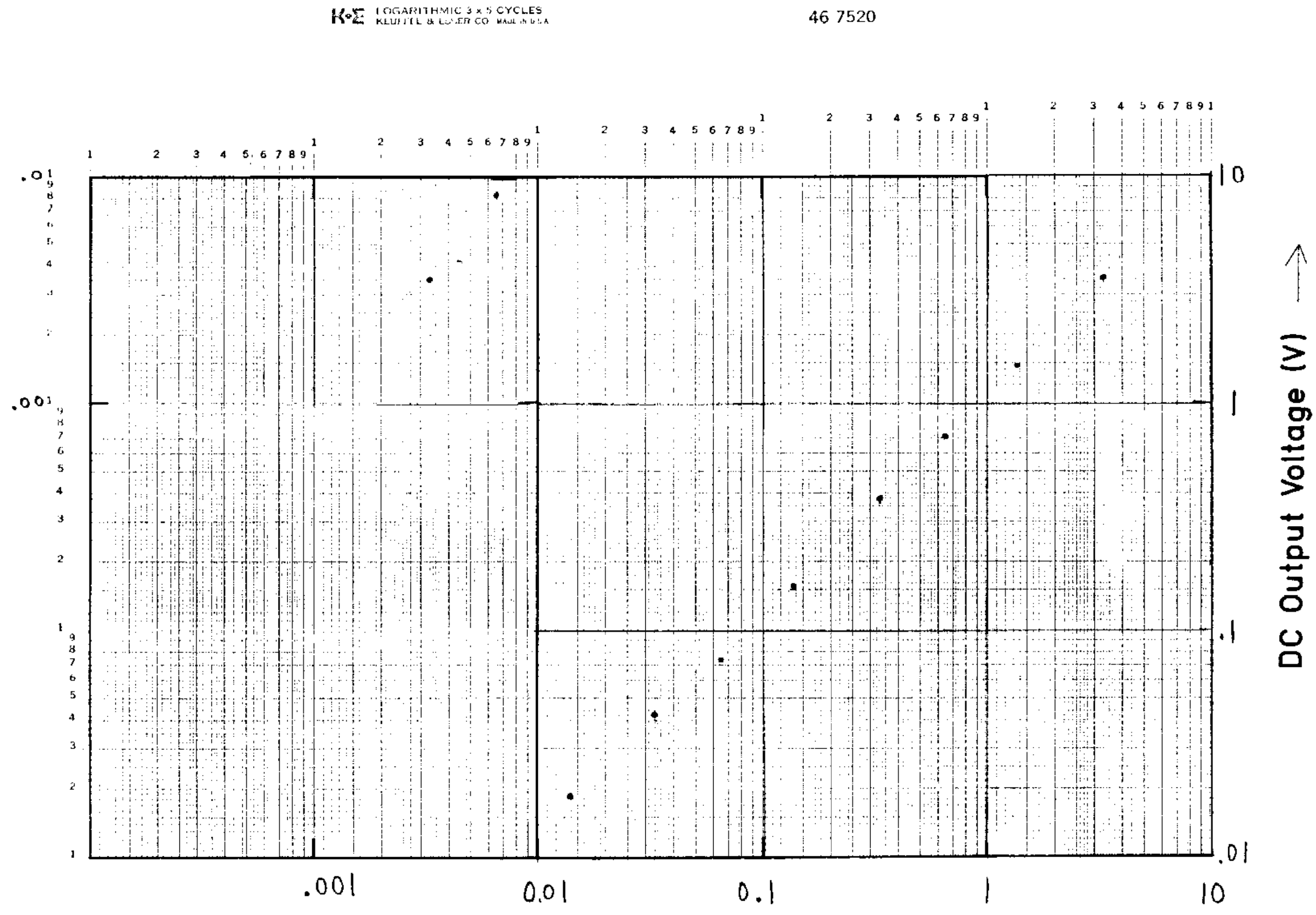

K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7520
.001
0.01
0.1
1
10
455kHz Input Voltage (V)p—p
DC Output Voltage (V)
.01
.1
1
10

Figure 4

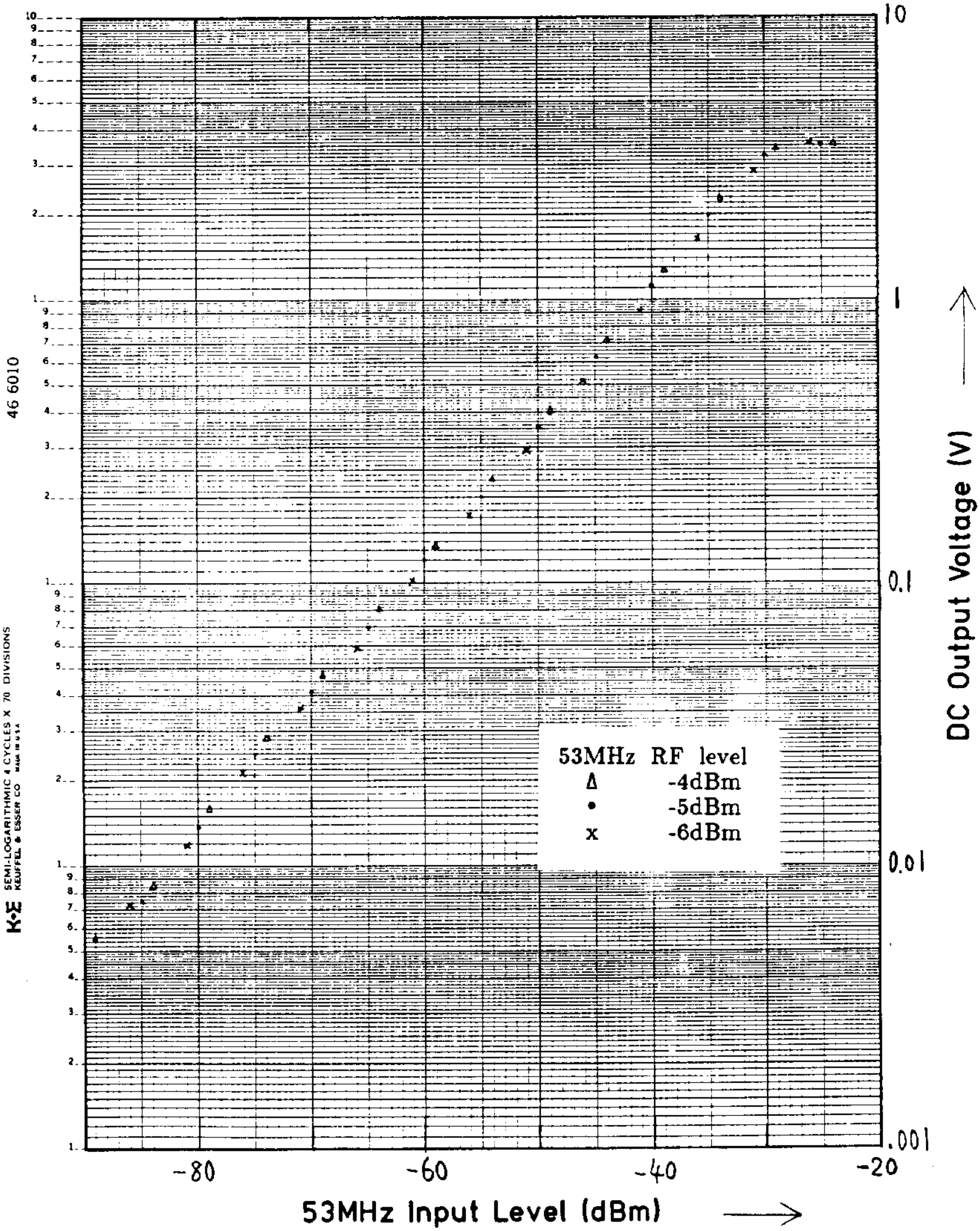
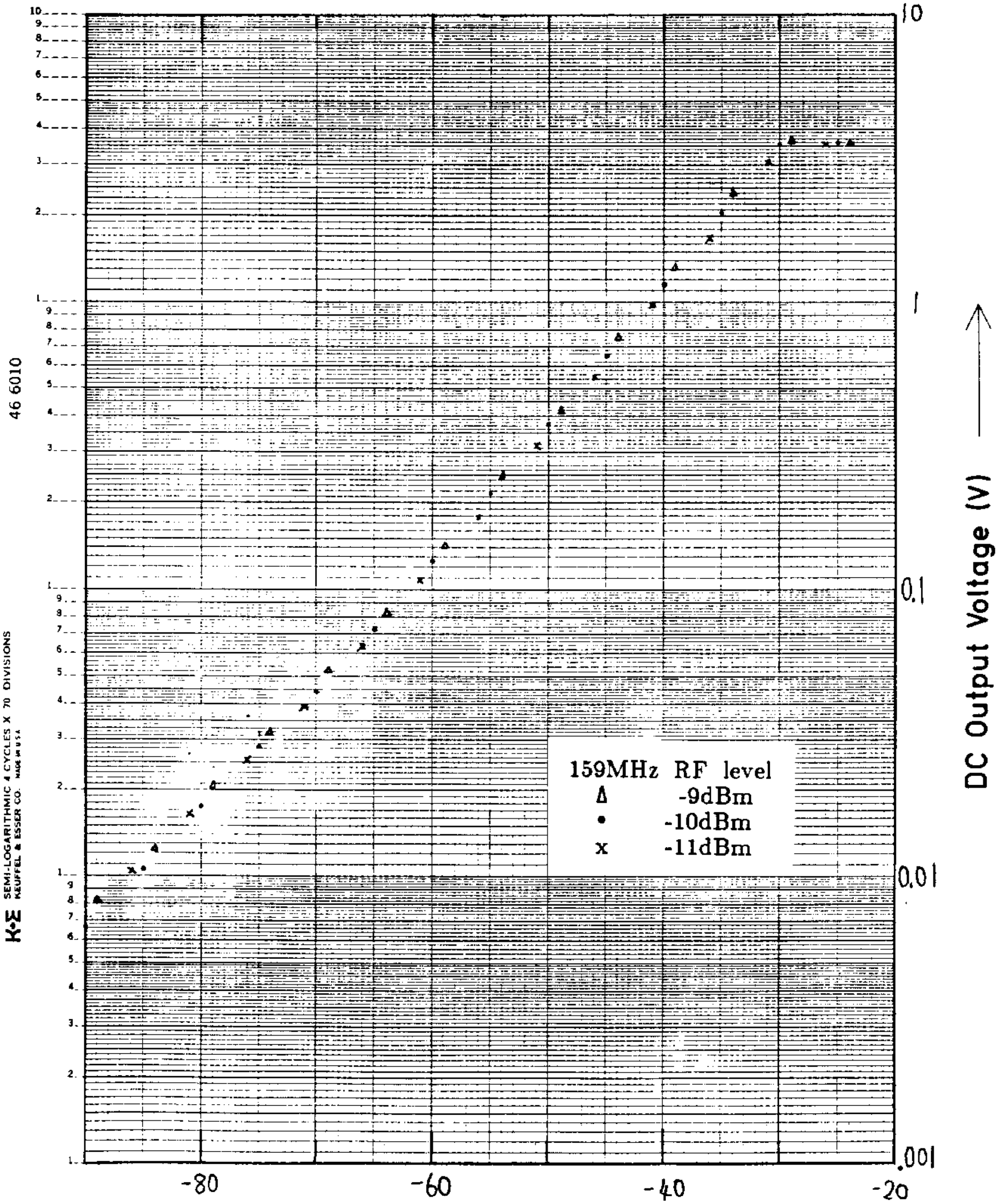

10
1
0.1
0.01
.001
-80
-60
-40
-20
53MHz Input Level (dBm)
DC Output Voltage (V)
53MHz RF level
Δ -4dBm
• -5dBm
x -6dBm
46 6010
K+E SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.

Figure 5



159MHz Input Level (dBm)

Figure 6

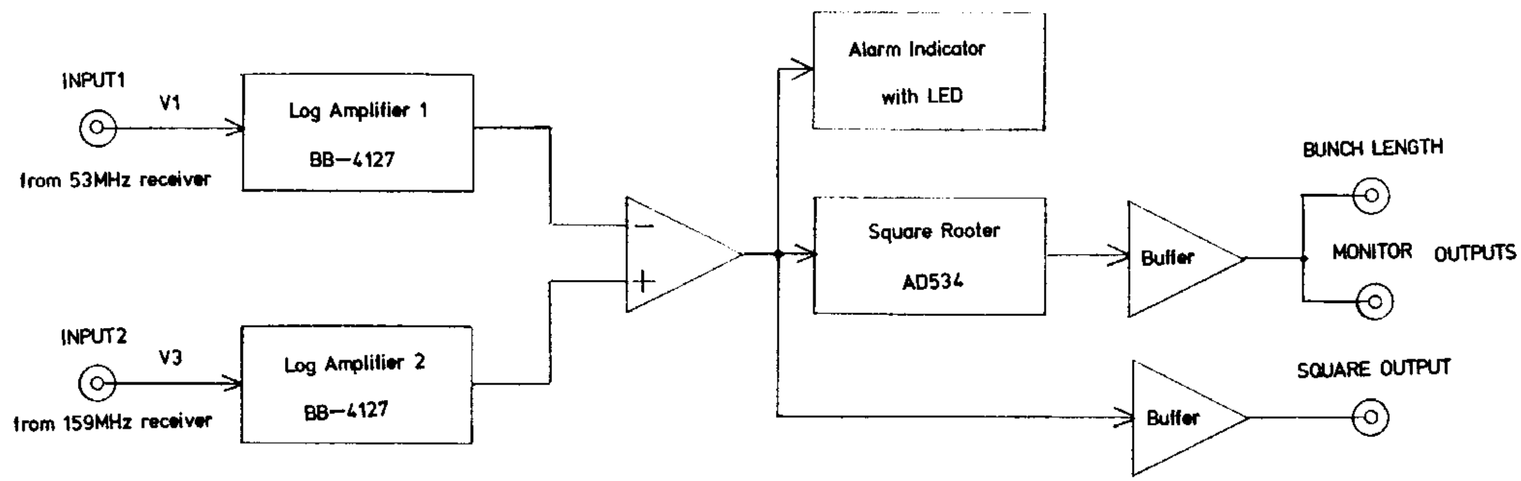
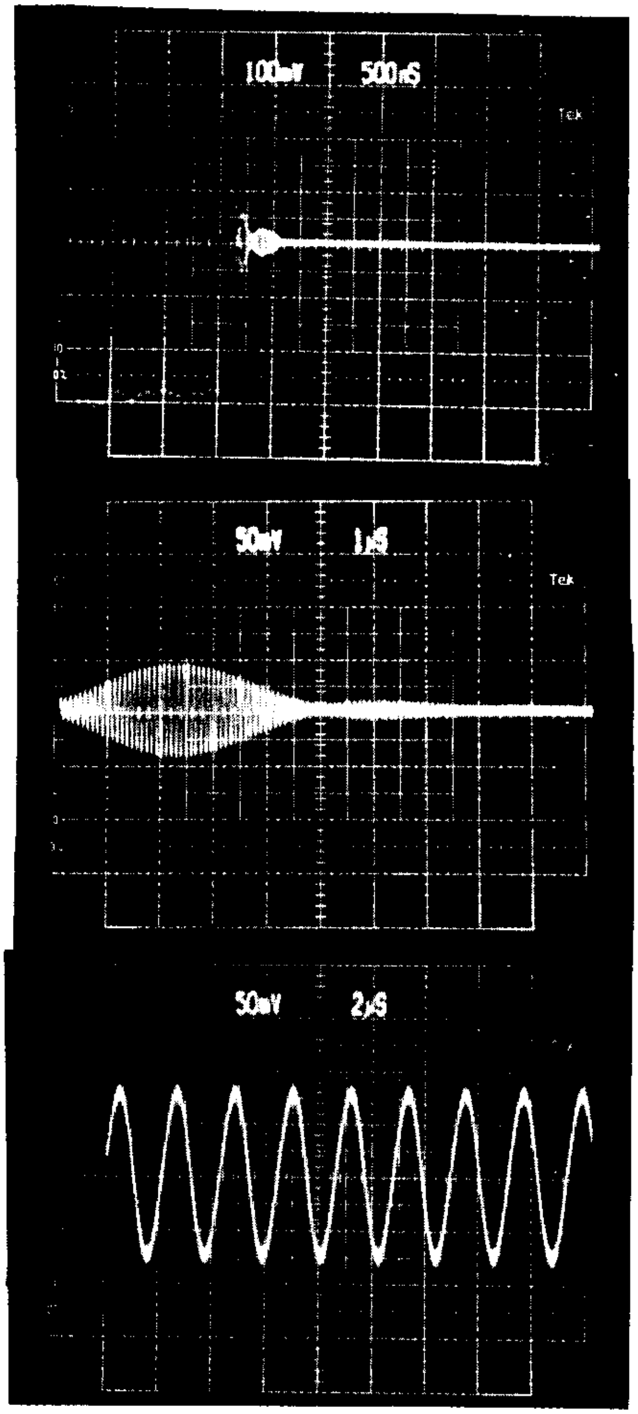

INPUT1
V1
from 53MHz receiver
INPUT2
V3
from 159MHz receiver
Log Amplifier 1
BB-4127
Log Amplifier 2
BB-4127
−
+
Alarm Indicator
with LED
Square Rooter
AD534
Buffer
Buffer
BUNCH LENGTH
MONITOR OUTPUTS
SQUARE OUTPUT

Figure 7



a)

b)

c)

Figure 8

CONSOLE LOCATION 11; RF-So   10-MAY-1989 15:06
Fast Time Plot

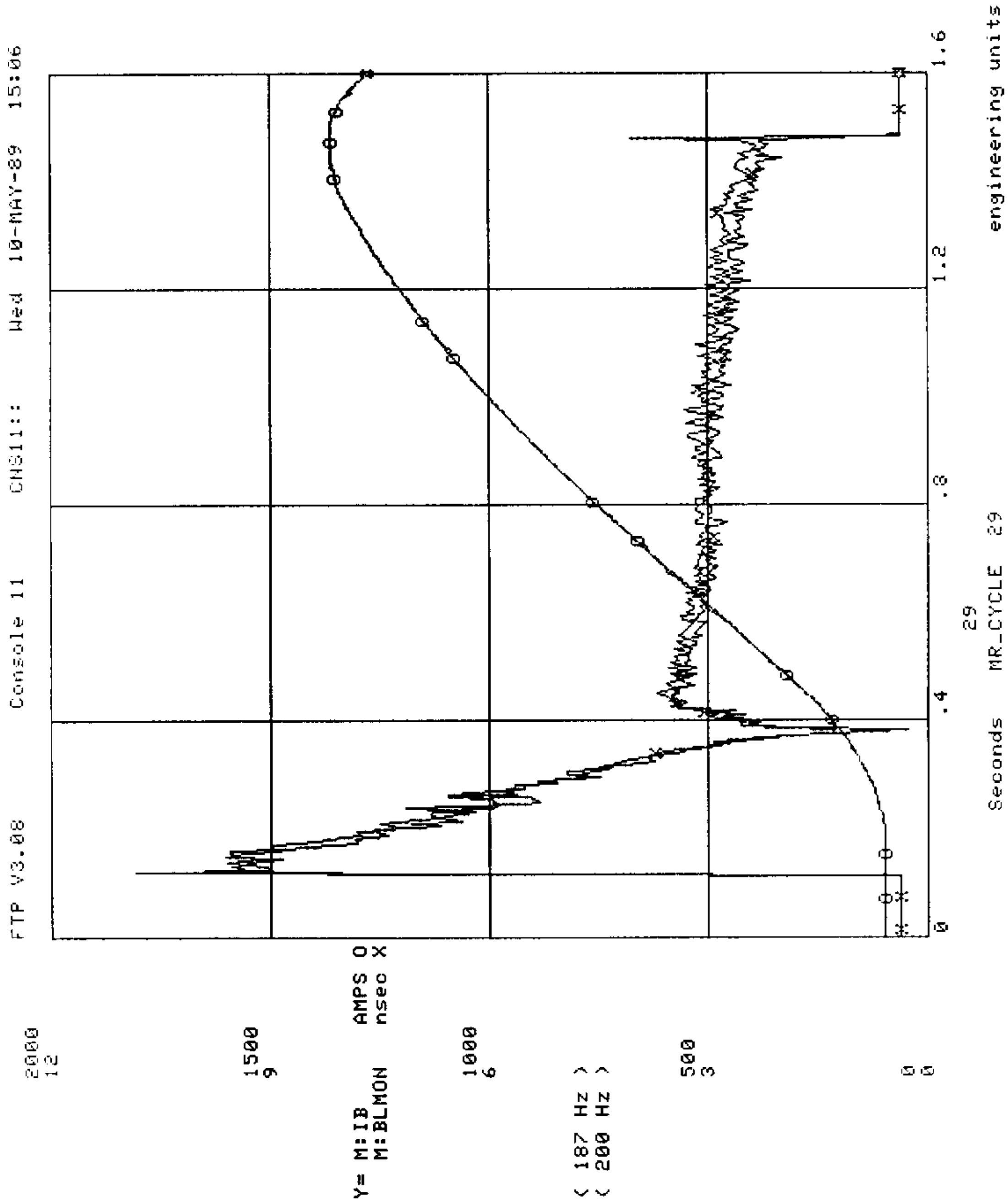
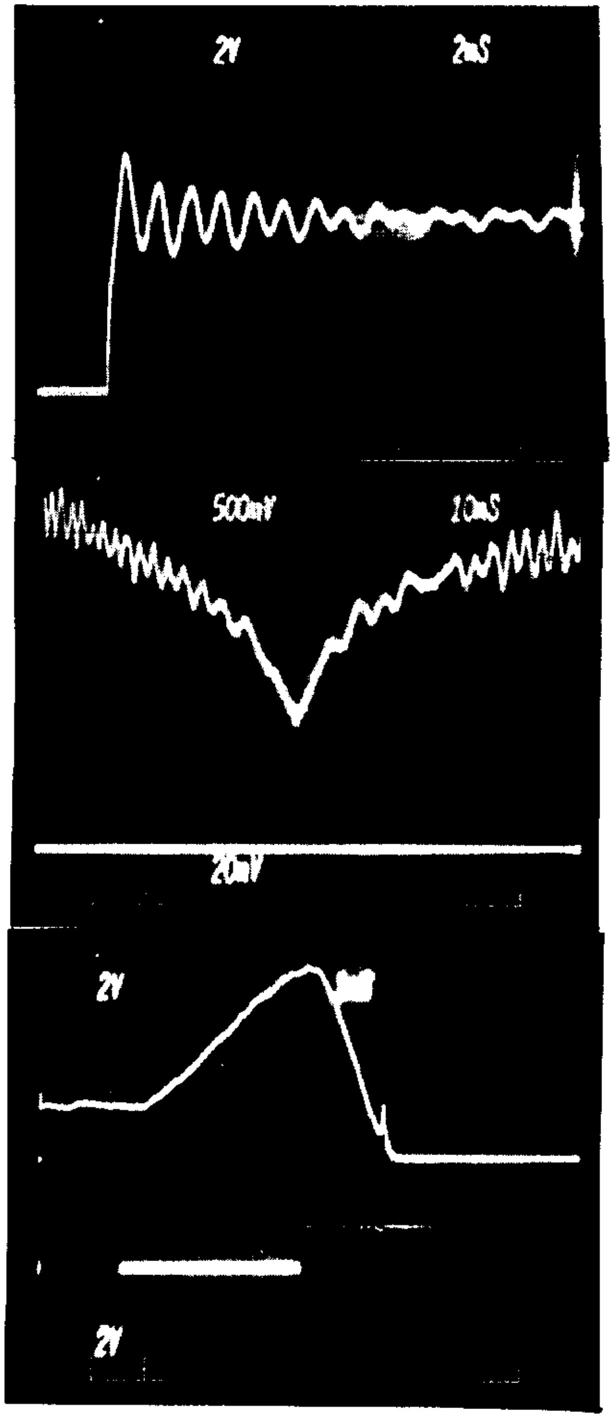


Figure 9



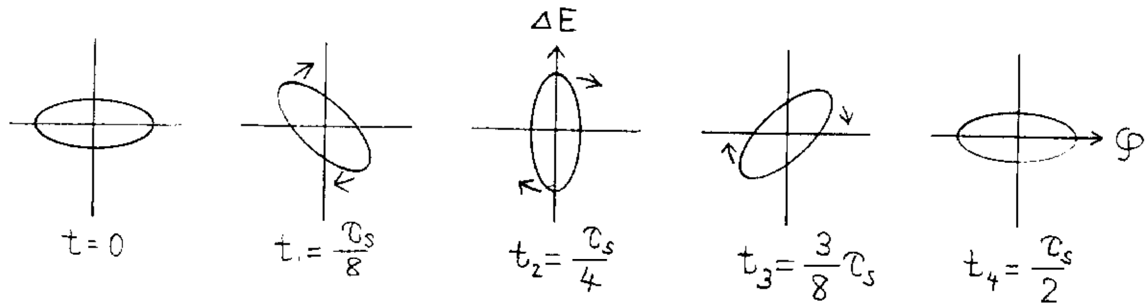
a)

b)

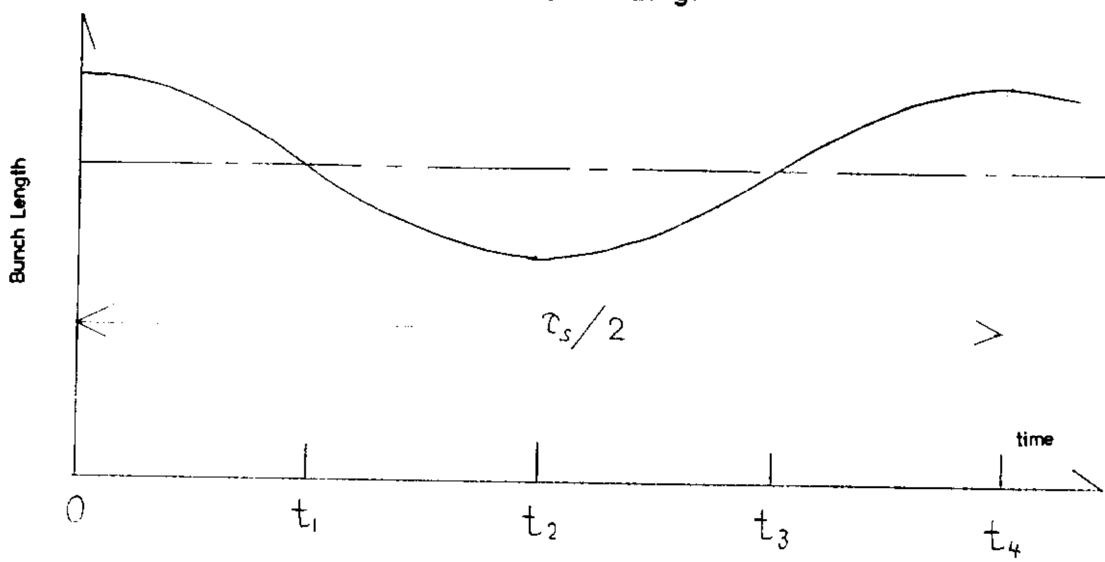
c)

Figure 10

Sampled Bunch Rotation in Phase Space



Modulation of Bunch Length

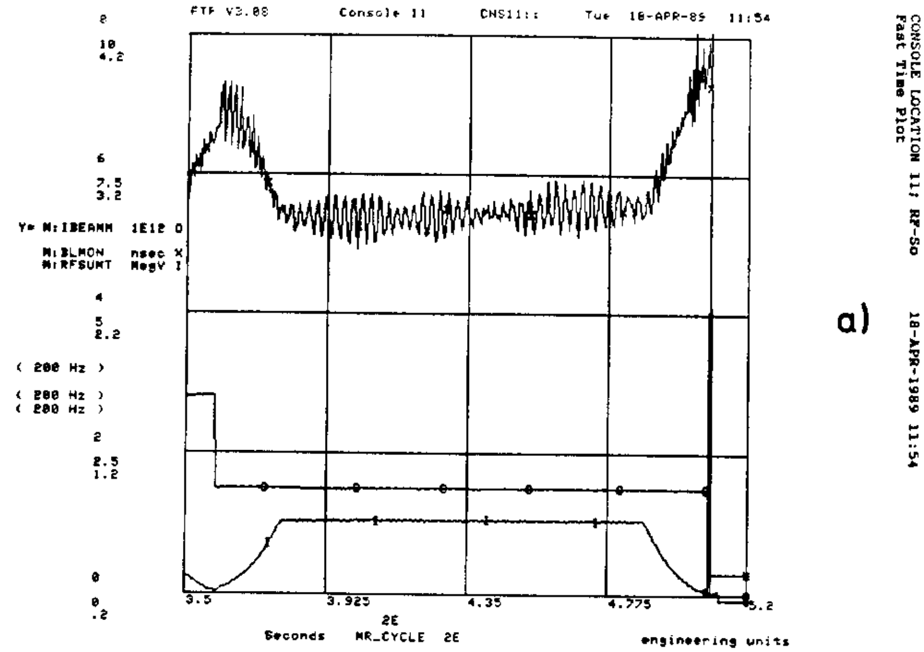


τ_s : synchrotron period

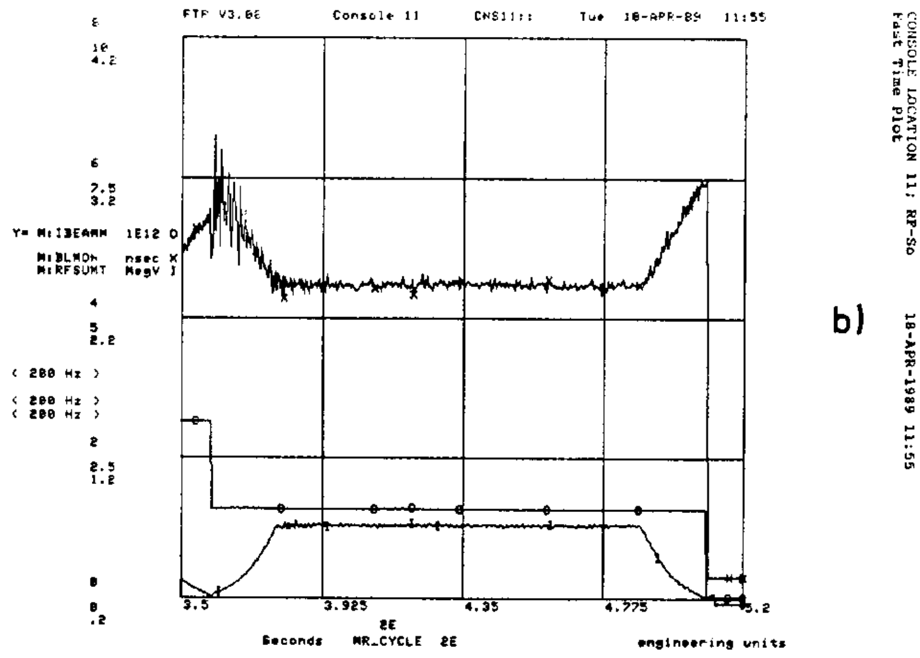
ΔE : energy deviation

φ : phase

Figure 11


FTP V3.08 Console 11 CNS11:: Tue 18-APR-89 11:54
Y= M:IBEAMM 1E12 O
M:BLMON nsec X
M:RFSUMT MegV I
(200 Hz)
3.5
3.925
4.35
4.775
5.2
Seconds MR_CYCLE 2E
engineering units
CONSOLE LOCATION 11; RF-So
Fast Time Plot
18-APR-1989 11:54

a)


FTP V3.08 Console 11 CNS11:: Tue 18-APR-89 11:55
Y= M:IBEAMM 1E12 O
M:BLMON nsec X
M:RFSUMT MegV I
(200 Hz)
3.5
3.925
4.35
4.775
5.2
Seconds MR_CYCLE 2E
engineering units
CONSOLE LOCATION 11; RF-So
Fast Time Plot
18-APR-1989 11:55

b)

Figure 12